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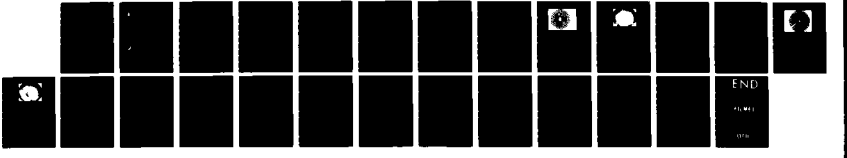

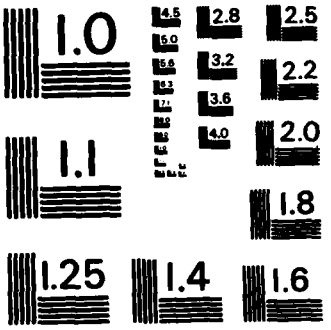

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TECHNICAL REPORT RR-85-2

TRANSLATION, ROTATION, SCALE AND ASPECT INVARIANT MATCHED FILTER AND SCENE COMBINATION

Don A. Gregory and James C. Kirsch
Research Directorate
Research, Development, and Engineering Center

June 1985

U.S. ARMY MISSILE COMMAND
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An interesting pattern has been discovered, which when used as the input scene to a Vander Lugt type correlator, possesses almost complete invariance to the usual problems associated with pattern recognition. The scene may be translated, rotated, scaled, or tilted without total loss of the correlation signal. This, of course, is a specialized scene, but interesting applications for such a pattern do exist.

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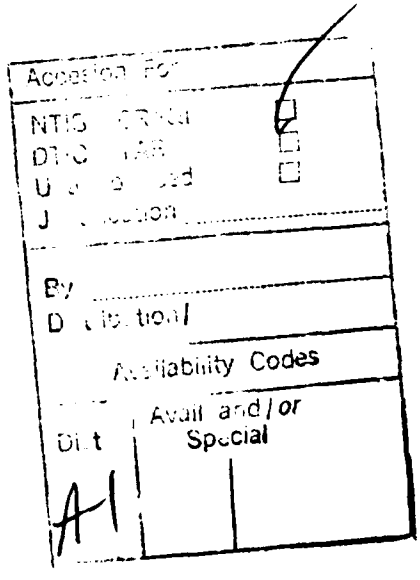

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I. INTRODUCTION AND THEORY

Many of the problems associated with coherent Fourier transform matched filters are well known [1] [2]. The autocorrelation signal detected is quite sensitive to the rotation, scale, and tilt of the scene to be recognized. The extent of the sensitivity is dependent upon the spatial frequency content of the scene [3]. The correlation signal is, however, translationally invariant; explained by the shift theorem of Fourier optics [4]. In specialized applications it would be advantageous to be able to recognize a predetermined scene for location identification. As an example, consider an aircraft landing without radar information. A scene, painted on the runway, could provide optical correlation information to the pilot in addition to the other information provided by ground personnel. Consider also the problems associated with landing a helicopter on a moving object, such as an aircraft carrier. A pattern on the landing (or hovering) location could provide automated information to the pilot about his general position. One can think of many other applications where such a pattern would be useful.

Several patterns were considered for this type of application, and two were investigated experimentally and found to be of possible use. The first pattern was a "spoked wheel" design (essentially an angular Ronchi ruling) consisting of black and white (or opaque and transparent) areas, separated by equal angles. A photograph is given in Figure 1. This scene was used as the input to a real-time optical correlator, sketched in Figure 2 and described in detail elsewhere [5]. The matched filter was recorded on a high resolution Kodak 649F plate and developed using standard procedures. A photograph of the filter is given in Figure 3. This is a Vander Lugt type correlator, therefore Figure 3 can also be viewed as the optical Fourier transform of the pattern given in Figure 1. The transmission function describing the pattern of Figure 4 [6]:

$$t(\theta) = [\text{Rect } (\frac{\theta}{\alpha}) * \text{Comb } (\frac{\theta}{2\alpha})] \tag{1}$$

In general

$$\text{rect } (z) = \begin{cases} 1 & |z| \leq \frac{1}{2} \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

and

$$\text{Comb } (z) = \sum_{n=-\infty}^{\infty} \delta (z-n) \tag{3}$$

The intensity recorded on the photographic plate can be written as: [7]

$$I \propto | F [t(\theta)] |^2 \tag{4}$$

where F denotes the Fourier Transform.

The form of Equation (1) lends insight into what this intensity should be: [8]

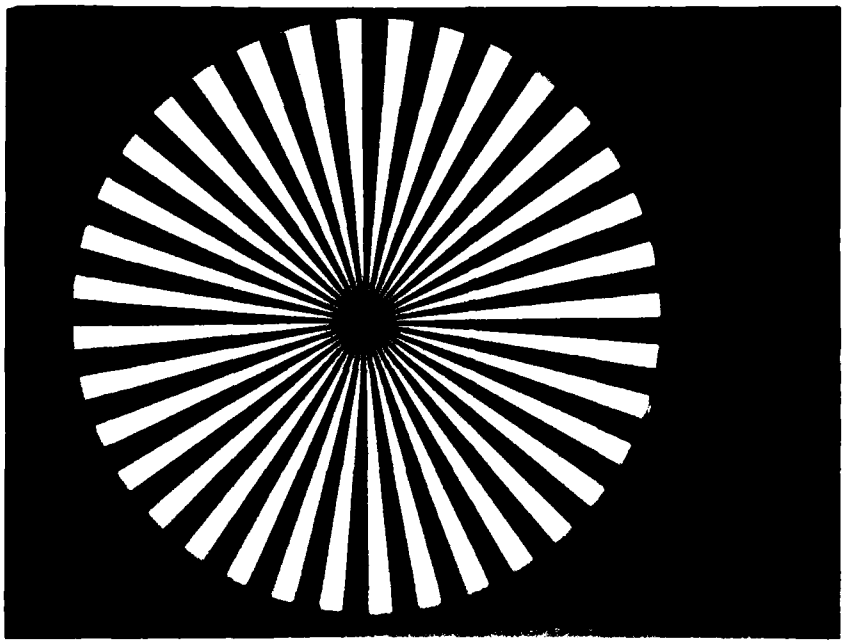

Figure 1. A photograph of the "spoked wheel" pattern (angular Ronchi ruling).

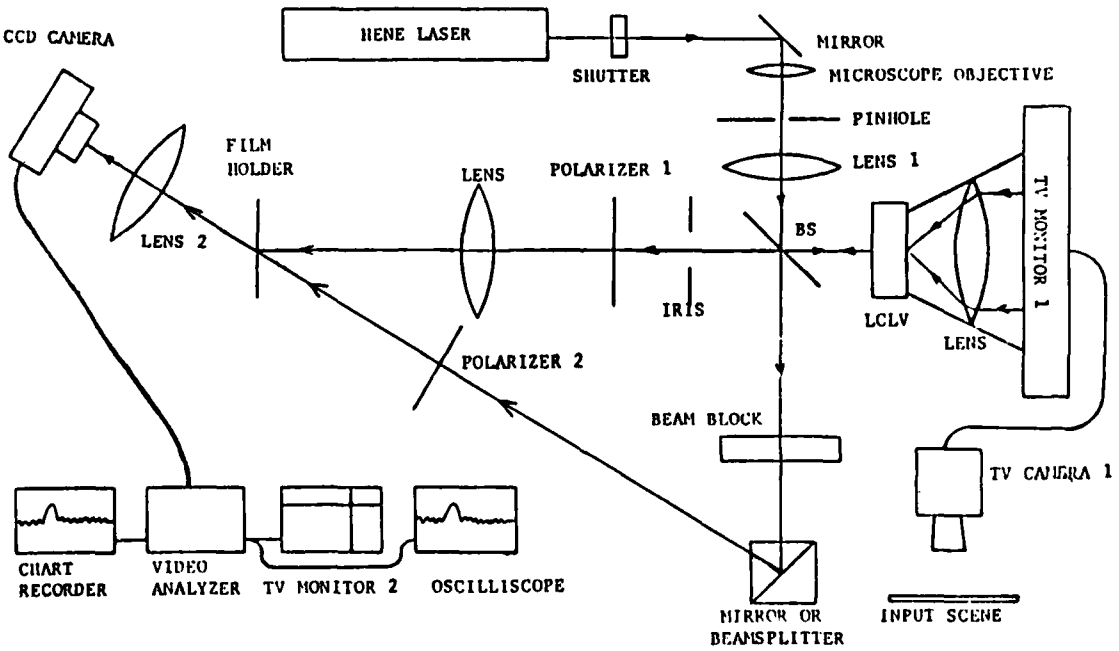

Figure 2. The real-time optical correlator - experimental arrangement.

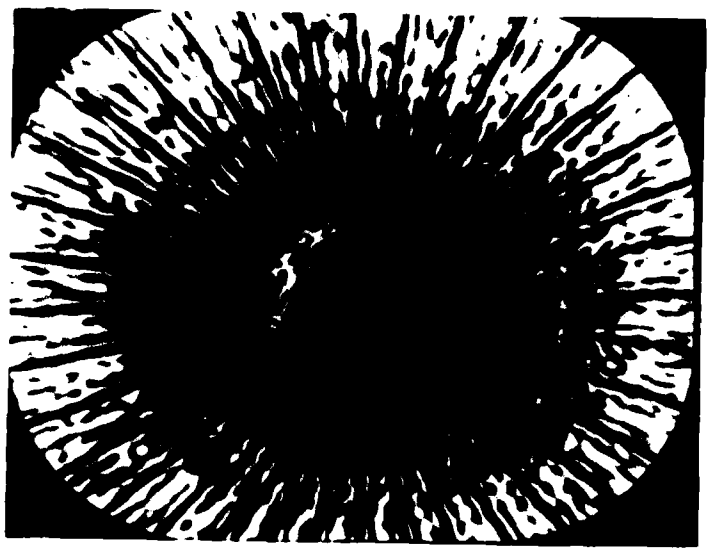

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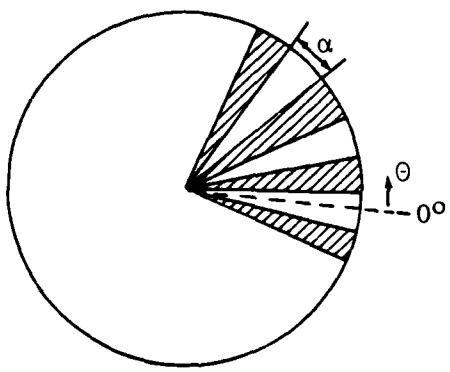
Figure 3. A photograph of the matched filter of the angular Ronchi ruling.



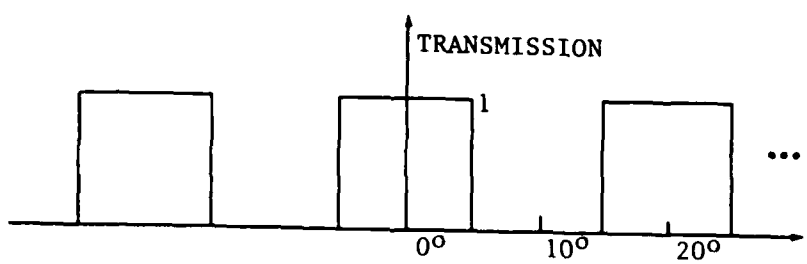


Figure 4. The transmission function for the angular Ronchi ruling.

$$F\left[\text{rect}\left(\frac{\theta}{\alpha}\right)\right] = \alpha\ \text{sinc}(\omega\alpha) \tag{5}$$

where

$$\text{sinc}\ (\omega\alpha) = \frac{\sin\ (\pi\omega\alpha)}{\pi\omega\alpha} \tag{6}$$

and ω is the angular spatial frequency. Also: [9]

$$F\left[\text{Comb}\left(\frac{\theta}{2\alpha}\right)\right] = 2\alpha\ \text{Comb}\ (2\omega\alpha) \tag{7}$$

and

$$\text{Comb}\ (2\omega\alpha) = \sum_{n=-\infty}^{\infty} \delta\ (2\omega\alpha - n), \tag{8}$$

which determines the allowed angular spatial frequencies:

$$\omega = \frac{n}{2\alpha} \tag{9}$$

The fundamental frequency is

$$\omega_f = \frac{1}{2\alpha}, \tag{10}$$

which appears to be reasonable when compared to the same formulation for a Ronchi ruling [10].

Thus the intensity pattern observed should consist of dark radial spokes (corresponding to the fundamental angular frequency), separated by the angle 2α (the inverse of ω_f), with lighter spokes on either side of the dark spokes (due to the sinc^2 term).

II. EXPERIMENTAL RESULTS

Matched filters, such as the one in Figure 3, were addressed with the angular Ronchi ruling pattern and the correlation signal observed with the TV camera shown in Figure 2. Tests were done for translation, rotation, scale, and aspect angle sensitivity. It was found that the scene did possess the usual translation invariance and was quite insensitive to scale and aspect angle changes. The scene was then rotated. The correlation signal decreased in intensity and completely disappeared after about $\pm$ 7 degrees of rotation. The 10-degree separation of the spokes in the matched filter was too great. To correct this problem, two possibilities existed. The angle α in the image could be halved so that the angle between the spokes in the matched filter would also be smaller by a factor of 2. Another idea which takes advantage of the symmetry of the optical Fourier transform proved to be a better solution [7]. Figure 5 is a photograph of a "phase" shifted angular Ronchi ruling pattern. It is produced by cutting two of the patterns of Figure 1 into two equal pieces each, then reassembling two of the halves. The transmission of such a pattern may be modeled with the use of Figure 6.

Let $t_1(\Theta)$ be the transmission function for the "A" pattern (see Equation (1)) and $t_2(\Theta)$ be the transmission for the "B" pattern. Then the transmission of the combined patterns may be written as:

$$T(\Theta) = t_1(\Theta) + t_2(\Theta) \tag{11}$$

The Fourier transform may then be written as:

$$F[T(\Theta)] = F[t_1(\Theta) + t_2(\Theta)] \tag{12}$$

$$= F[t_1(\Theta)] + F[t_2(\Theta)] \tag{13}$$

Both terms of Equation (13) produce fundamental radial spokes in the Fourier transform plane separated by the angle 2α, but the spokes corresponding to the "A" pattern are displaced angularly from the spokes due to the "B" pattern. The amount of displacement corresponds to the angle α - the amount of shift in the photograph of Figure 5. Therefore, the Fourier transform of Figure 5 should look very similar to Figure 3; with twice the number of spokes. The matched filter actually obtained is shown in Figure 7. The separation between spokes is α, (5 degrees).

This matched filter/scene combination was then tested for translation, rotation, scale, and aspect angle correlation sensitivity. As expected, the scene could be linearly translated with little or no loss in signal. The input scene was then rotated 360 degrees. The correlation signal decreased only slightly through the entire rotation. This is shown in Figure 8. A large improvement was seen over the "unshifted" pattern. The correlation signal did decrease in intensity, but only about 25 percent over the entire 360 degrees of rotation. A large correlation is still present at any rotational position.

In previous experiments, the sensitivity to a change in scale of the input scene has been observed and found to be a serious limitation[11]. The "shifted" angular Ronchi ruling and matched filter were tested to observe the

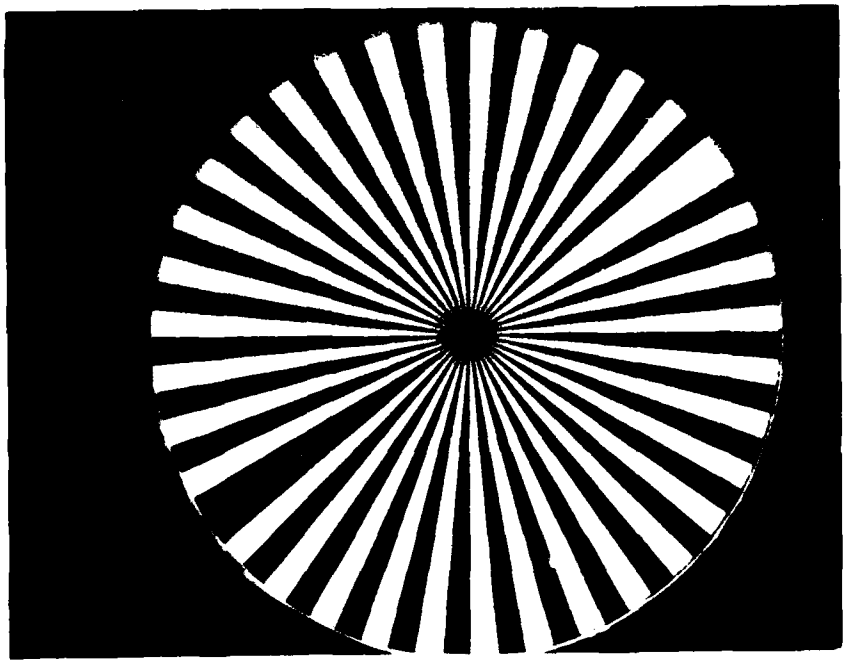


Figure 5. A photograph of the "phase shifted" angular Ronchi ruling.

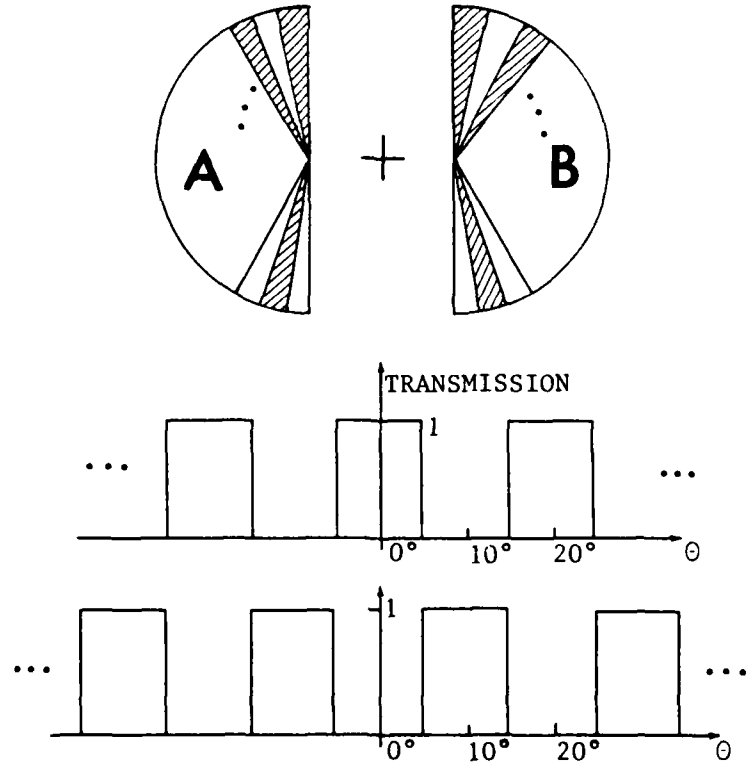


Figure 6. The transmission function for the "phase shifted" Ronchi ruling.

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Figure 7. A photograph of the matched filter of the "phase shifted" angular Ronchi ruling.

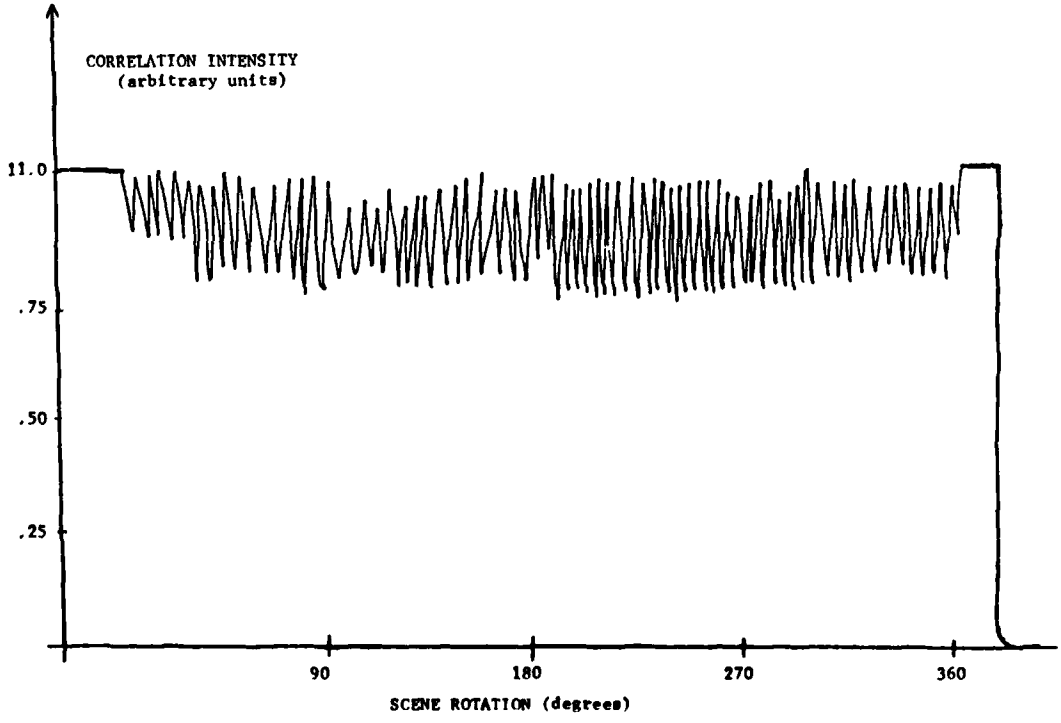

Figure 8. Correlation intensity vs rotation of the "phase shifted" angular Ronchi ruling input scene.

variation in correlation intensity as the size of the input scene image was changed using a motorized zoom lens. The magnification factor ranged from about .5 to about 2.5. A plot of the intensity of the correlation signal as a function of the magnification is given in Figure 9. The range of magnification was as large as possible using the zoom lens available. For a magnification of about .5, the television image covered about one-third of the monitor, or about 170 TV lines, and for a magnification of about 2.5, the overall image was not very intense, which the liquid crystal light valve could not respond to very efficiently [12]. This problem could have been avoided, perhaps, by incorporating an automatic iris and gain control in the television camera.

The final test consisted of changing the aspect angle (tilt) of the scene as the correlation signal was observed and recorded. It is known that, for many scenes, the correlation signal is not as sensitive to aspect angle changes as it is to rotation and magnification. Figure 10 gives the correlation intensity as the scene was tilted from +45 degrees through 0 degrees to -45 degrees. The filter was made at 0 degrees tilt. The decrease in correlation is not critical for a very large aspect angle. Even at the two extremes of aspect, the signal is still present; and, although down in intensity an order of magnitude, still maintains a good signal to noise ratio. The scene must be tilted by about $\pm$20 degrees before the correlation signal decreases by 50 percent.

In an actual application, the previous parameters (translation, rotation, scale, and tilt) may all change simultaneously. It was possible to do this simulation and the results appear promising. The signal was lost only for large aspect angles combined with maximum scale changes. Rotation and translation were not serious limitations.

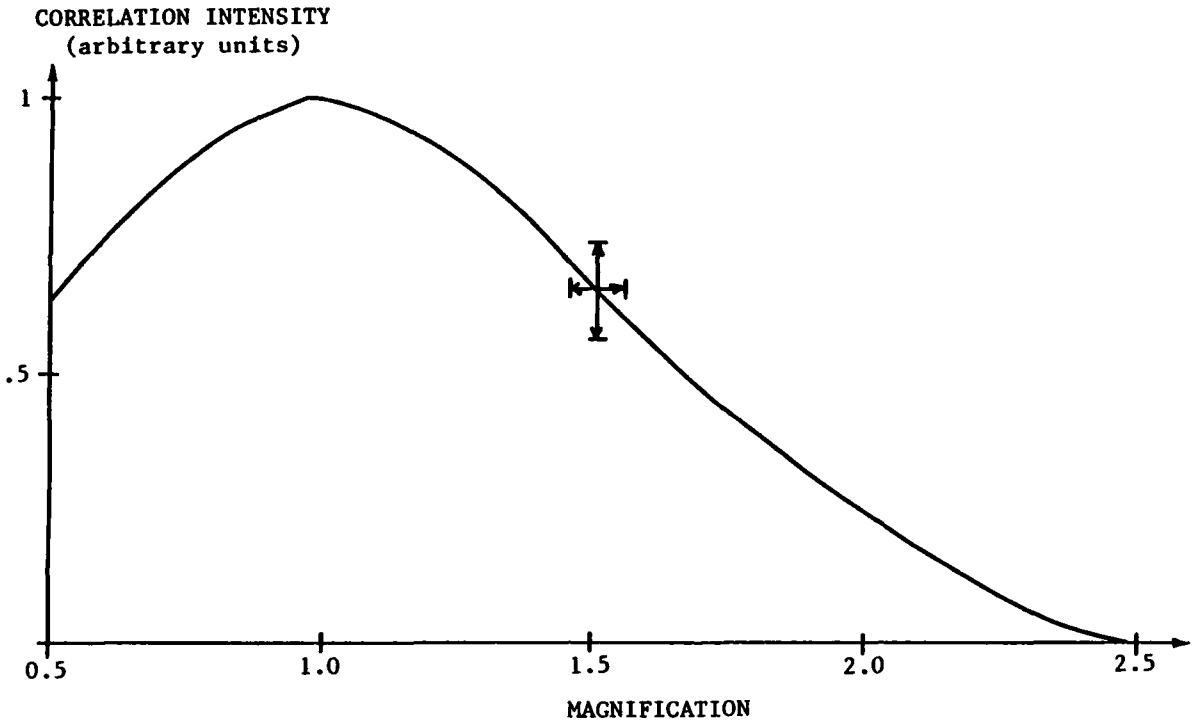

Figure 9. Measured correlation intensity vs magnification for "phase shifted" angular Ronchi ruling.

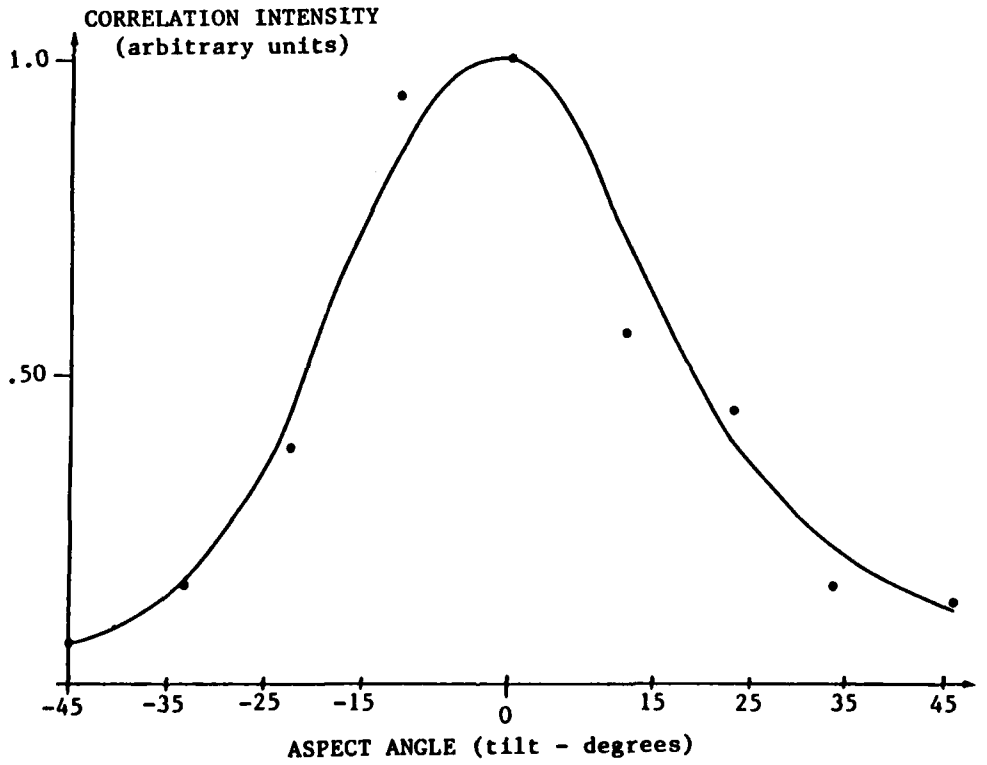

Figure 10. Measured correlation intensity vs aspect angle for "phase shifted" angular Ronchi ruling.

III. CONCLUSIONS

The ideas and results presented in this report show promise - perhaps a solution waiting for a problem. The "shifted" angular Ronchi ruling matched filter has demonstrated a much greater tolerance of parameter changes than more usual patterns. The usual translational invariance is present, as should be expected, and the correlation signals also are quite insensitive to a rotation, magnification, or tilt of the angular ruling scene. The initial success of this experiment is promoting further investigations using this type scene. Many of the results presented here can probably be improved upon by maximizing parameters used in making the matched filters, such as reference to object beam ratios, exposure times, etc. The fundamental angular spatial frequency of the scene should also be maximized so as to provide the lowest loss in correlation intensity while still preserving the uniqueness of the matched filters. Angular Ronchi ruling with a high fundamental spatial frequency (small angle spokes) could not be resolved at a distance (scale change), while rulings with extremely low fundamental frequencies (large angle spokes), would not preserve the desired rotational invariance.

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